# Radiation Shielding Simulation For Interplanetary Manned Missions

S. Guatelli[1], B. Mascialino[1], P. Nieminen[2], M.G. Pia[1]

[1]INFN Genova, Italy

[2]ESA-ESTEC, The Netherlands

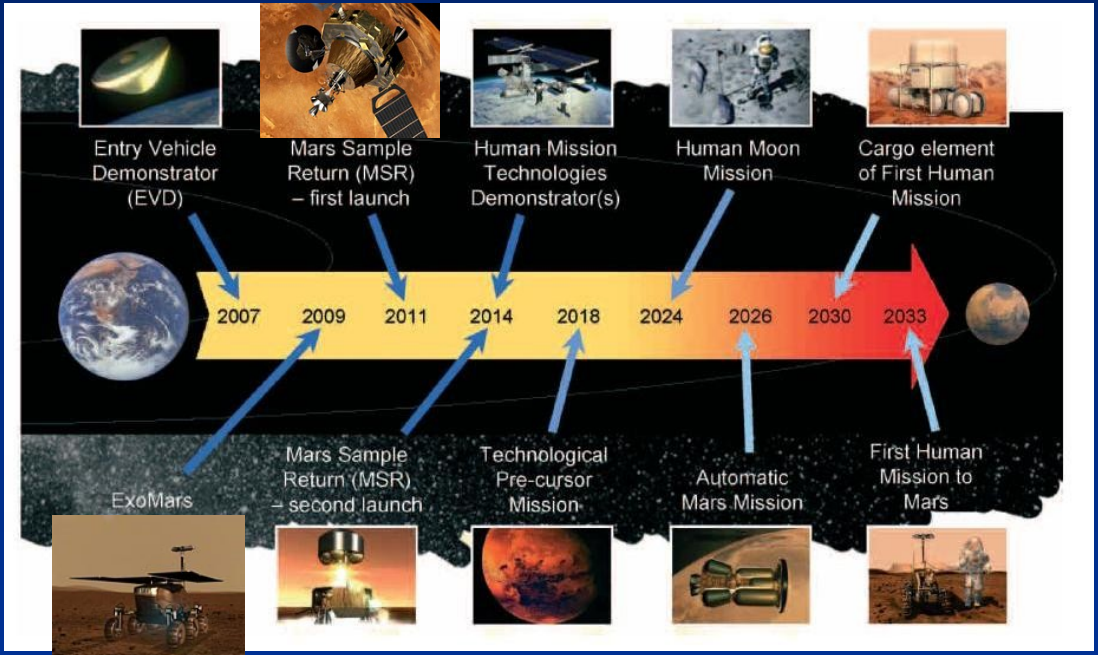


**IPRD 06**
**10th Topical Seminar**
**on Innovative Particle and Radiation Detectors**
**1 - 5 October, 2006**
**Siena, Italy**

Susanna Guatelli

# Context

- Planetary exploration has grown into a major player in the vision of space science organizations like ESA and NASA
- AURORA: European long term plan for the robotic and human exploration of the solar system
  - with Mars, the Moon and the asteroids as the most likely targets



# Human missions to Mars

The **effects of space radiation on astronauts** are an important concern

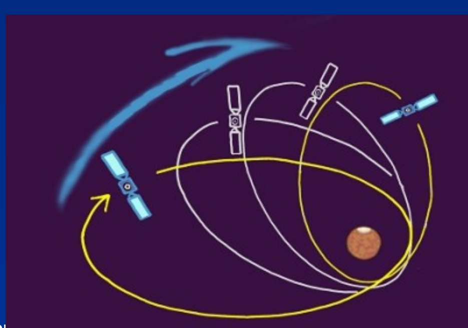
Mission to Mars → ~ 2.5 year total duration

- **6 month** transit from the Earth to Mars
- **1.5 year** stay on the Martian surface
- **6 month** return to the earth

The crew is exposed to the space radiation environment →

- Radiation sickness
- Damage to the central nervous system
- Cancer

Optimize trajectories



**Shielding**


# This project

**In the framework of the AURORA programme of ESA**

**Scope**

Quantitative evaluation of the physical effects of space radiation in interplanetary manned missions

Transfer vehicles

On planetary surface

First **quantitative** evaluation of the shielding properties of **conceptual designs**

Comparison among different shielding options

**Guidelines** for future **mission design** and concrete **engineering studies**

# Strategy

**Risk assessment**

- Reliable model to evaluate **acceptable risk**
  *(risk is not measured, it is **predicted** by a model)*

**Sound physics results**

- Distinguish **physical** and **biological** effects
- **Validation** of the physics modelling components
- Control **systematics**
- Quantitative **mathematical analysis** of results

**Advanced technology**

- **Object Oriented** technology
- Rigorous **software process**
- Software **tools** based on modern technology

**Transparency**

- **Open source** software tools
- Publicly distributed software

All the features above are relevant to a **mission-critical long-range** space science project

# Uncertainties and systematics

**Large uncertainties**

- Radiation environment
- Mission trajectories and duration
- Characteristics of spacecrafts
- Biological effects of radiation exposure

**Modelling hadronic interactions**

- Intrinsic complexity of the underlying theory
- Scarce and imprecise experimental data
- Monte Carlo codes still evolving in this domain

Focus on **physics** in the 1st study cycle

*Biological effects on top of sound physics in a following cycle*

**Relative** comparison of shielding configurations

*Instead of absolute dose calculations*

Multiple hadronic models to evaluate **systematics**

# Software Strategy

## Software Development Process

- Iterative and incremental model
- Based on the Unified Process
- Specifically tailored to the project
- Mapped onto ISO 15504

## Object Oriented Technology

- Openness to extensions and evolution
- Maintainability over a long time scale

### Monte Carlo simulation

- Model radiation environment
- Model shielding configuration
- Track particles in matter

Geant 4

**Functionality**
*(geometry, physics, interactivity)*

**OO** technology

Rigorous **validation**

### Physical Analysis

Evaluate energy deposited in the astronaut

AIDA

**Abstract Interfaces** for Data Analysis

Independence from any specific analysis tools

### Statistical Analysis

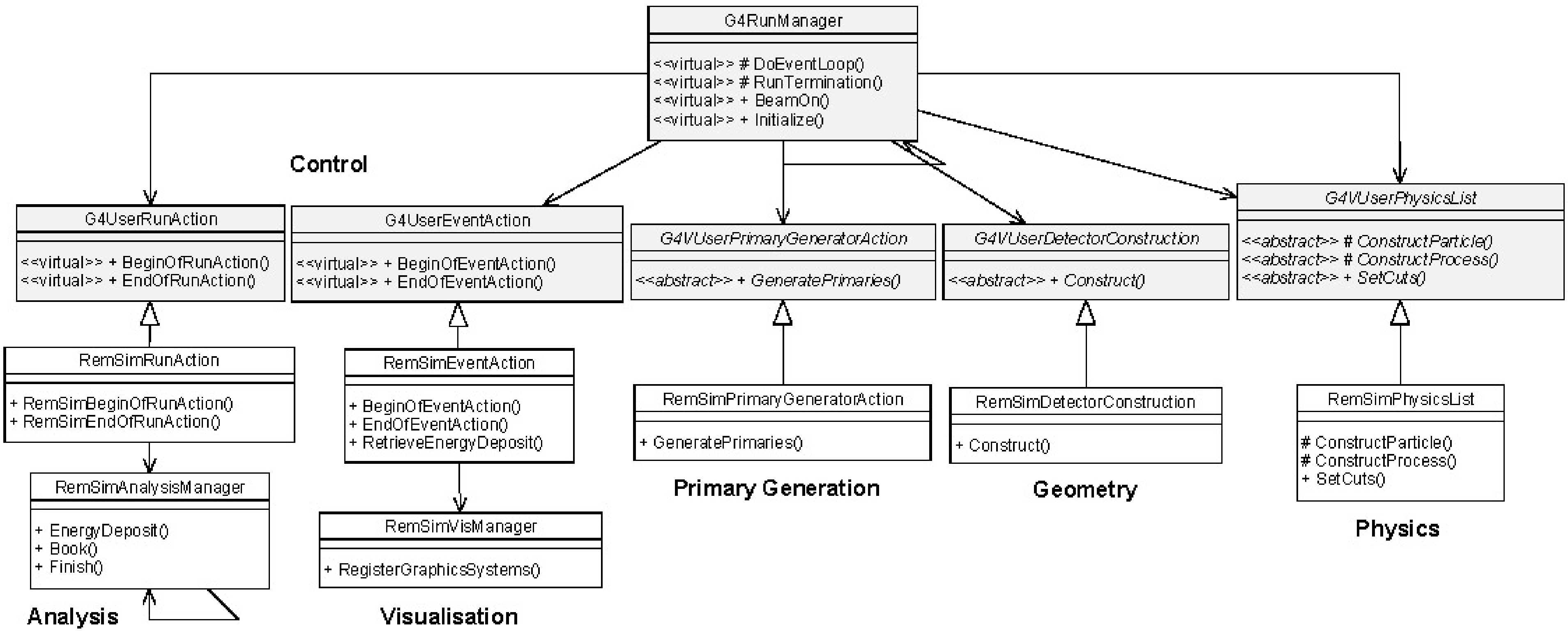
Compare shielding options quantitatively

Statistical Toolkit

Richest collection of **goodness-of-fit** tests for data comparison

AIDA compliant

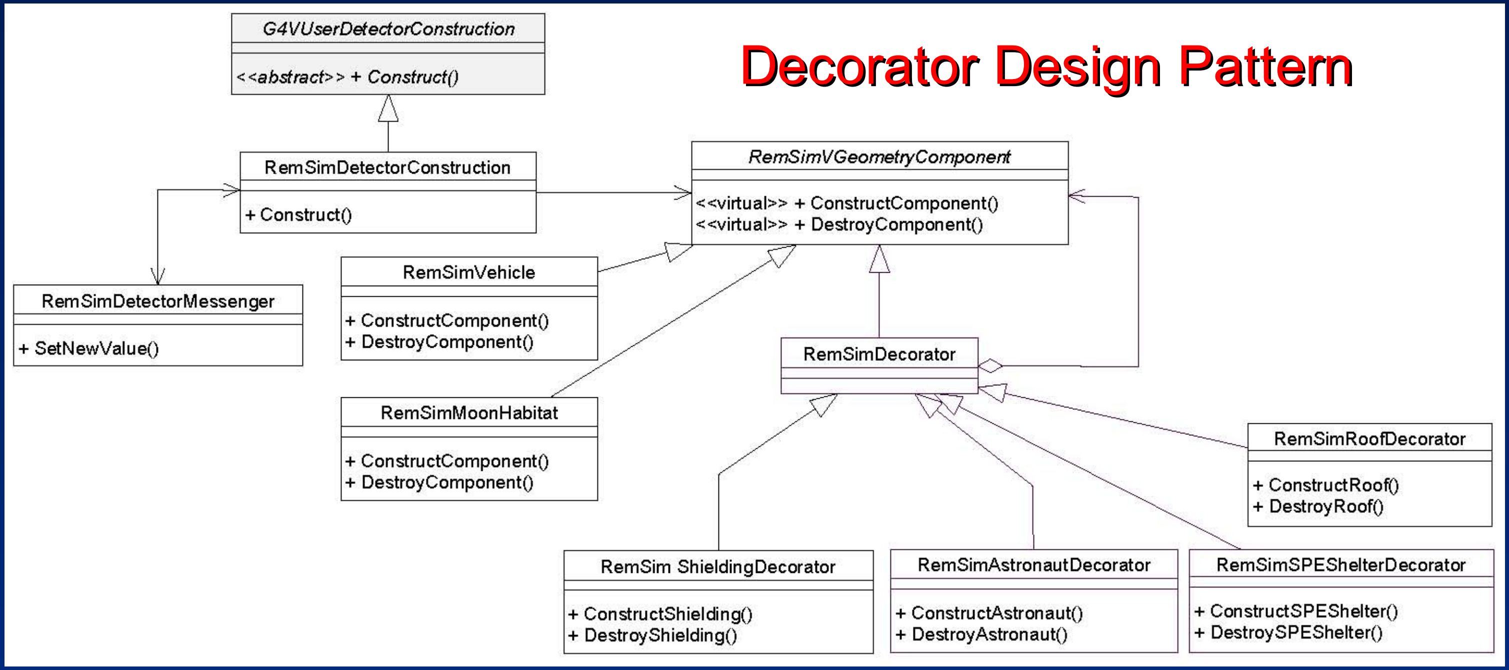
# Architecture of the Geant4 application




**Component-based architecture**

- Each component has a specific responsibility
- Flexibility, extensibility and maintainability

# Geometry and materials




Dynamically configure the simulation with

- Habitat type
- Shielding geometry
- Material
- Astronaut's location

# Primary particle generation

## Conservative assumptions for risk assessment

**CREME96**

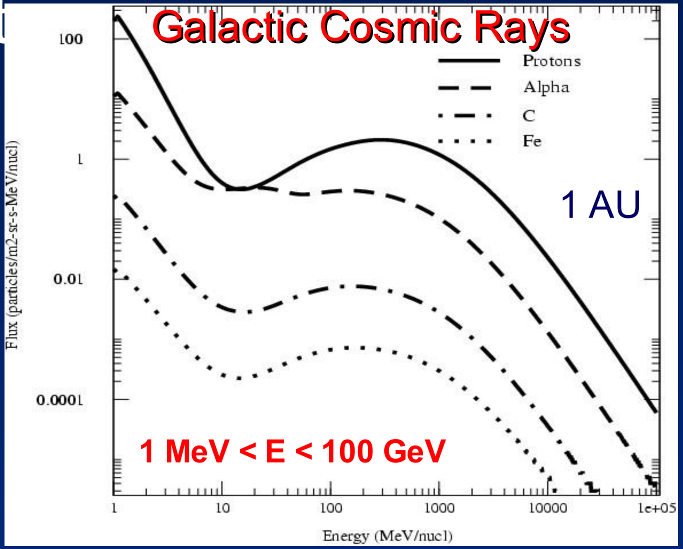
Radiation environment models
ECSS standard

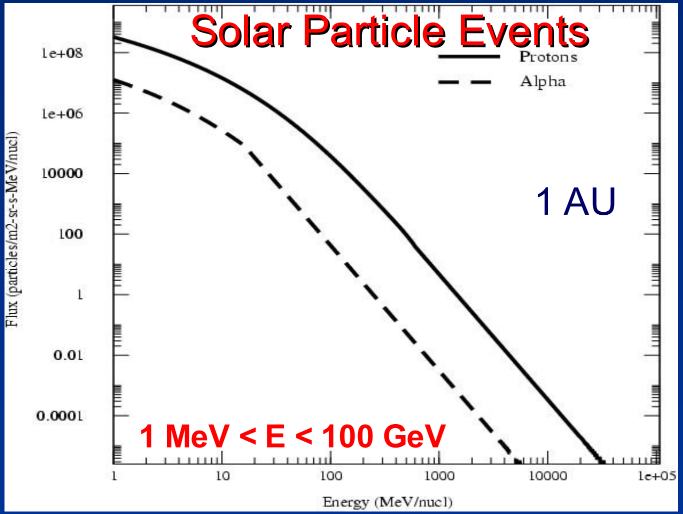
**Galactic Cosmic Rays**

- 1977 solar minimum
- Anti-correlation with solar activity

**Solar Particle Events**

- October 1989 event
- 99% worst case



# Physics modelling

## Electromagnetic physics

- Geant4 Low Energy Package for:
  - p, , ions (model based on ICRU49 parameterisation)
  - photons and electrons (model based on the Livermore Libraries)
- Geant4 Standard Package for positrons and muons
- Low Energy Electromagnetic Package → overall better accuracy
  - Demonstrated by validation studies

## Hadronic Physics

- Elastic and inelastic hadronic scattering
- Alternative models of the inelastic scattering of protons, neutrons, pions:

| Hadronic inelastic process | Binary set | Bertini set |
|---|---|---|
| **Low energy** range<br>*(cascade + preequilibrium + nuclear deexcitation)* | **Binary Cascade + Precompound + Deexcitation**<br>*( up to 10. GeV )* | **Bertini Cascade**<br>*( up to 3.2 GeV )* |
| **Intermediate energy** range<br>*( up to E = 25 GeV)* | **Low Energy Parameterised** | |
| **High energy** range<br>*( 20. GeV < E < 100. GeV )* | **Quark Gluon String Model** | |

- inelastic scattering
  - Low Energy Parameterized model up to E = 100 MeV
  - Binary Ion model

# Shielding studies

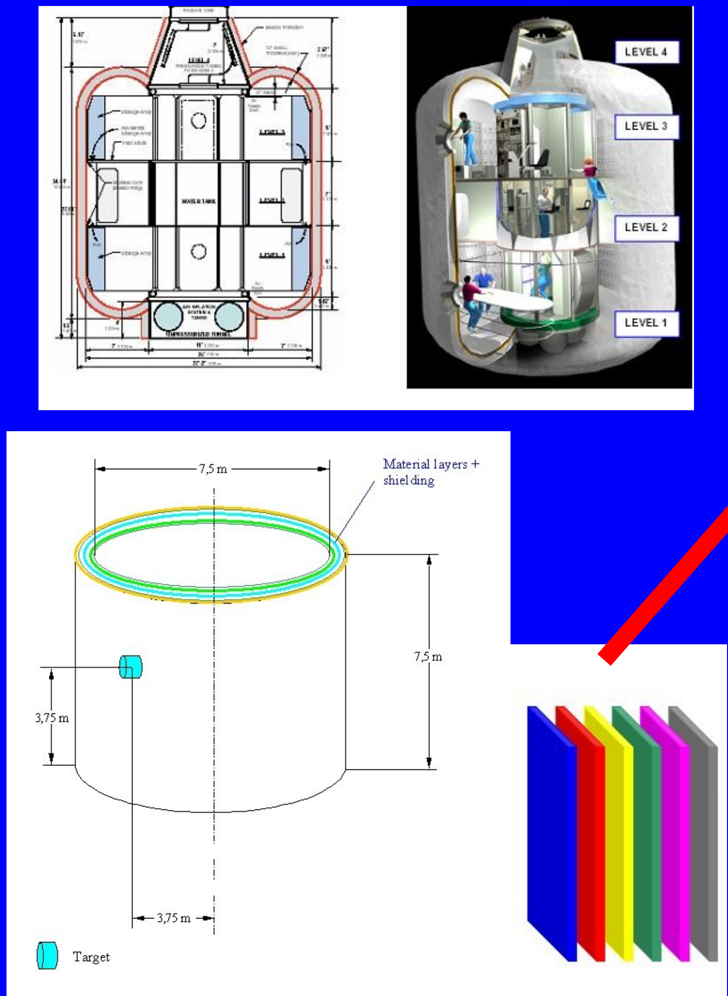
**Inflatable Habitat**

- Shielding materials
- Shielding thickness
- Comparison to rigid habitats

**Planet surface habitats**

- Shielding with lunar regolith
- Comparison to a rigid habitat

# Inflatable habitat

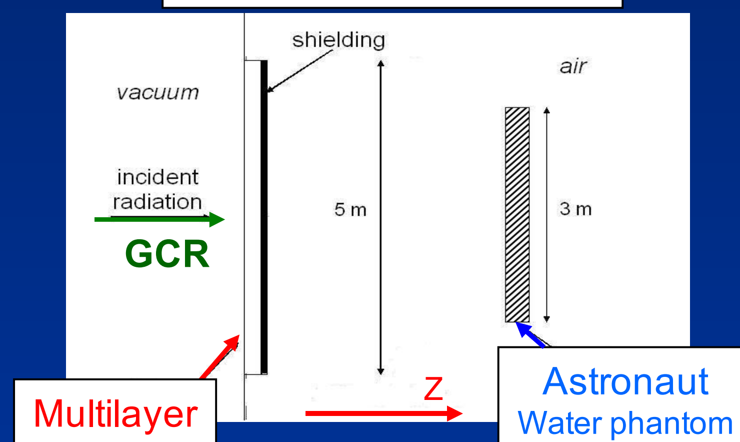



Engineering model by ALENIA SPAZIO

## Multilayer structure

- External **thermal protection** blanket
  - *Betacloth and mylar*
- **Meteoroid** and **debris** protection
  - *Nextel (bullet proof material) and open cell foam*
- Structural layer
  - *Kevlar*
- Rebundant bladder
  - *Polyethylene, polyacrylate, EVOH, kevlar, nomex*

### Experimental set-up




Simplified geometry
Retains the **essential characteristics** for a shielding characterization

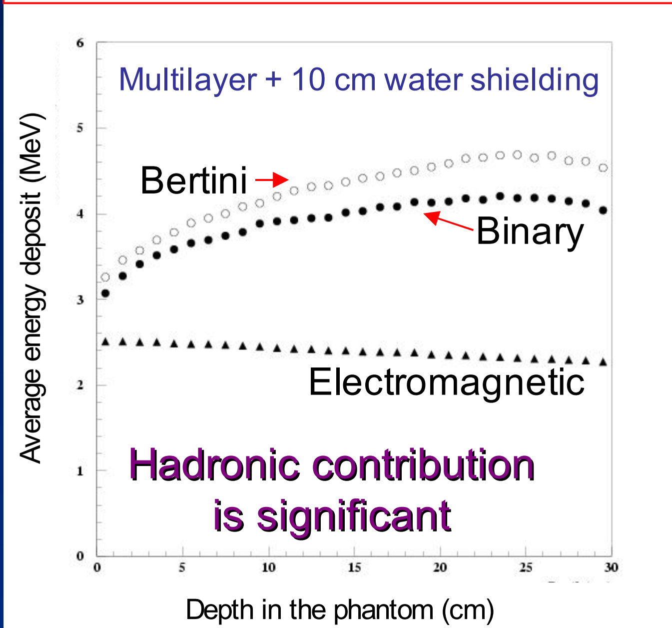
Susanna Guatelli

# Systematics of hadronic modelling

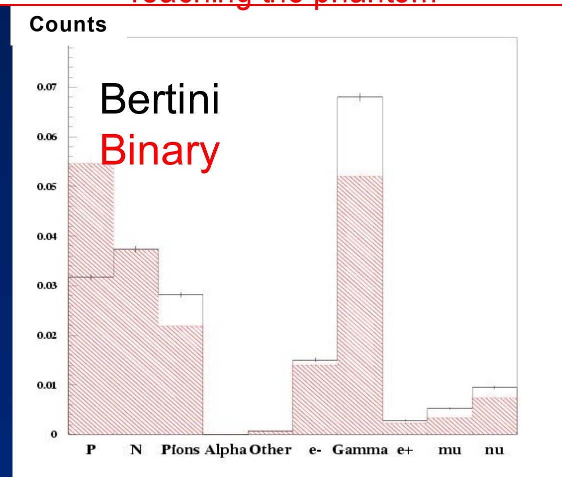
Study of possible **systematic effects** related to hadronic physics modelling

Comparison of the energy deposit in the phantom with different hadronic models

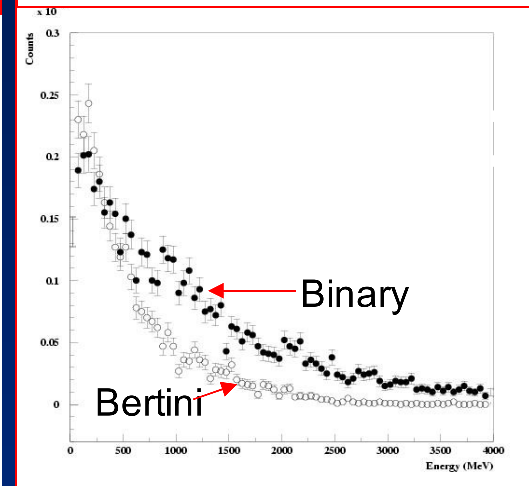
**Energy deposit profile of GCR proton**




Average no. of secondary particles reaching the phantom




**Energy of secondary p**




Different energy deposit profiles and secondary product patterns

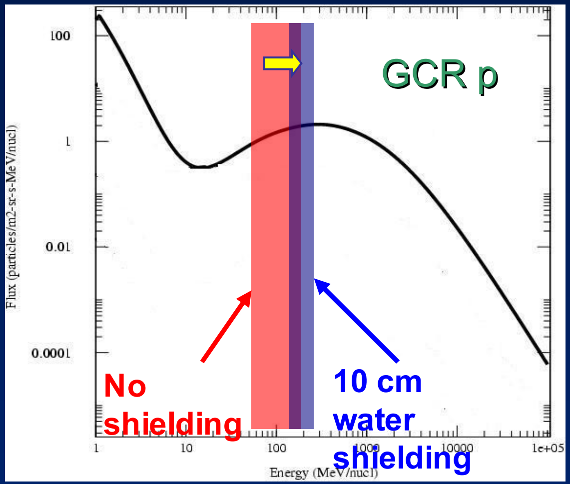
Kolmogorov Smirnov Test: **p-value < 0.05**

| Physics models | Energy deposit in the phantom |
|---|---|
| Electromagnetic | 71.9 ± 0.2 MeV |
| Hadronic-Bertini | 128.0 ± 0.4 MeV |
| Hadronic-Binary | 117.3 ± 0.4 |

~10 % difference **compatible** with **experimental validation** of Geant4 hadronic models

# Shielding thickness

Impossible to shield galactic cosmic rays completely!




The shielding modulates the fraction of GCR reaching the phantom

Secondary particles are also generated in the shielding material

Effect of **5 cm** and **10 cm water shielding** + inflatable multi-layer

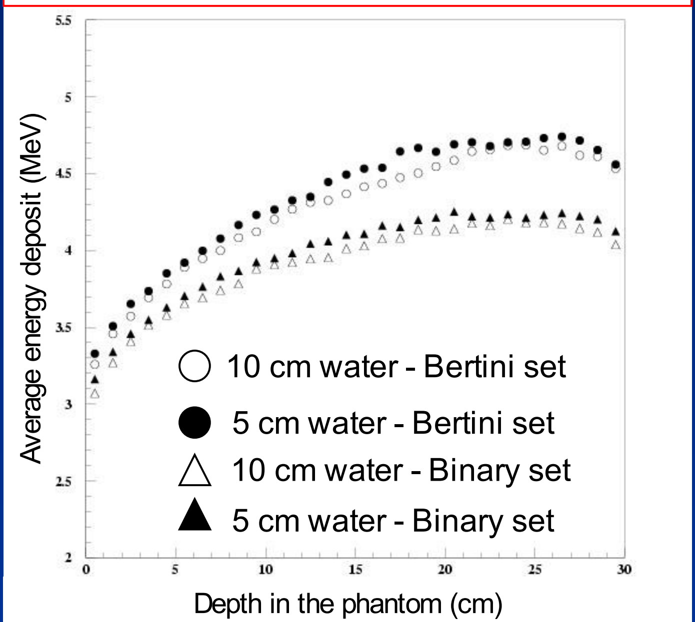
% GCR p reaching the phantom

| | 5 cm water | 10 cm water |
|---|---|---|
| EM + Bertini | 88.7 ± 0.2 | 83.3 ± 0.2 |
| EM + Binary | 88.0 ± 0.2 | 82.3 ± 0.2 |

Energy deposit in the phantom

| | 5 cm water | 10 cm water |
|---|---|---|
| EM + Bertini | 130.2 ± 0.5 | 128.0 ± 0.5 |
| EM + Binary | 119.3 ± 0.4 | 117.3 ± 0.4 |

Average energy deposit of GCR p in the phantom



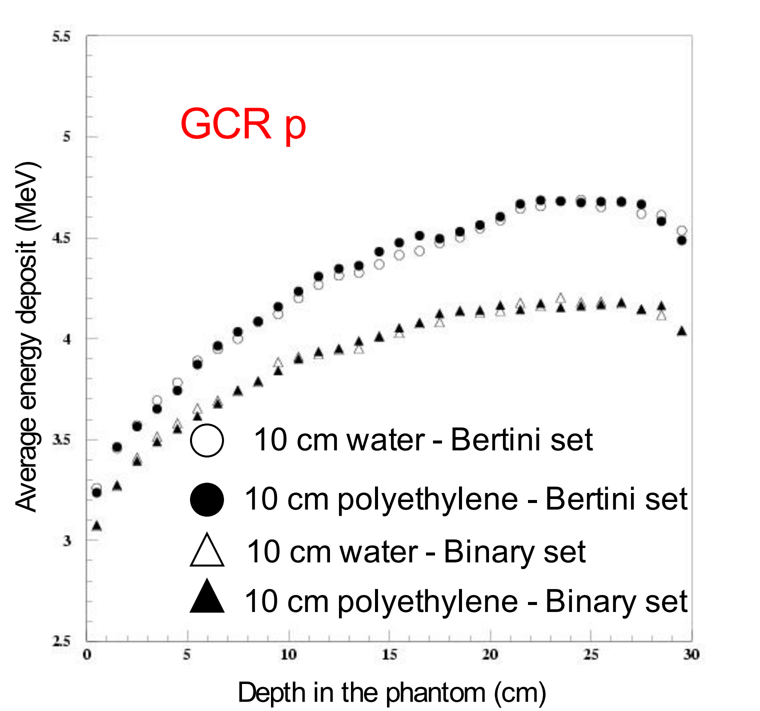

Doubling the shielding thickness results in:

- **Few % difference** in the stopped GCR protons
- **~2 % difference** in the total energy deposit

# Shielding material for an inflatable habitat

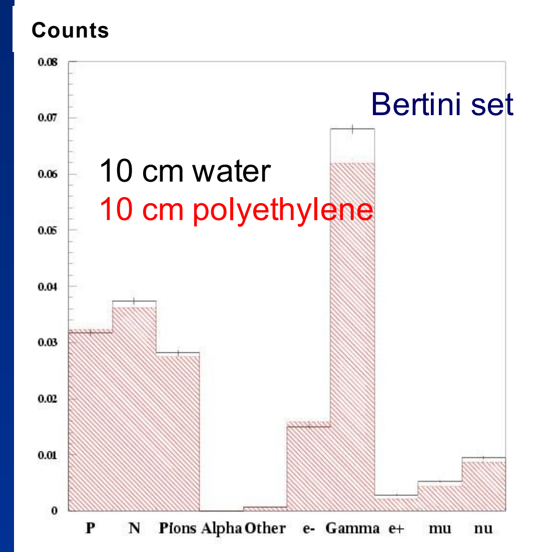
**Polyethylene** **Water**

Average energy deposit of GCR p

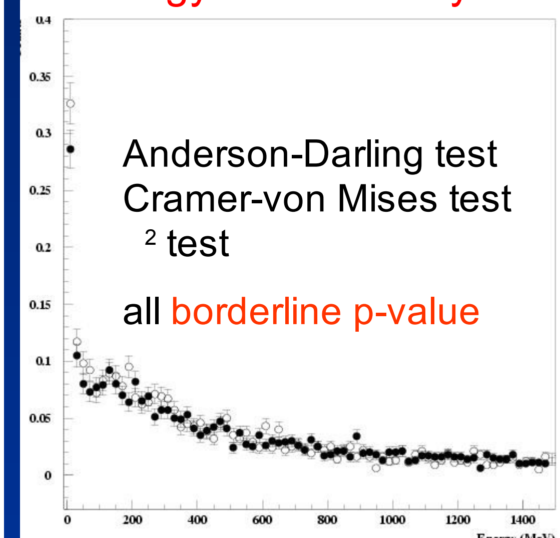



| Energy deposit in the phantom (MeV) | 10 cm polyethylene | 10 cm water |
|---|---|---|
| EM + Bertini | 128.4 ± 0.5 | 128.0 ± 0.5 |
| EM + Binary | 117.3 ± 0.5 | 117.3 ± 0.5 |

Average number of secondary particles reaching the phantom




Energy of secondary n



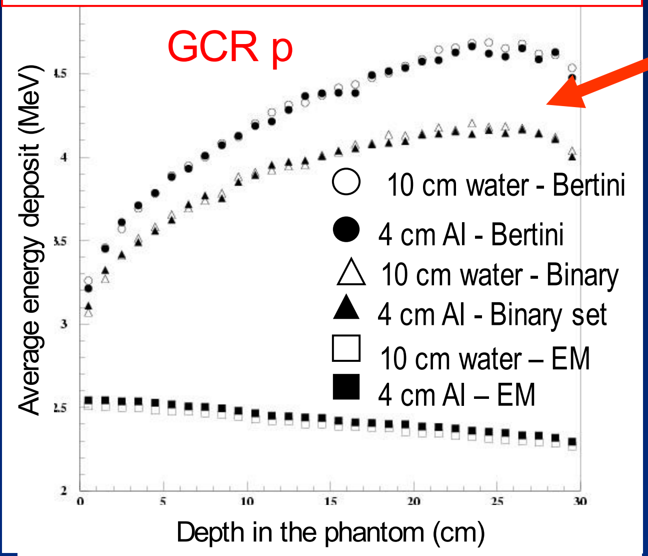

Water and polyethylene:

**equivalent shielding** effect

# Inflatable vs. Rigid Habitat

Reference: rigid structures as in the ISS (2 - 4 cm Al)

**Average energy deposit of GCR p**




Kolmogorov-Smirnov test

- Multi-layer + 10 cm water *equivalent to* 4 cm Al
- Multi-layer + 5 cm water *equivalent to* 2.15 cm Al

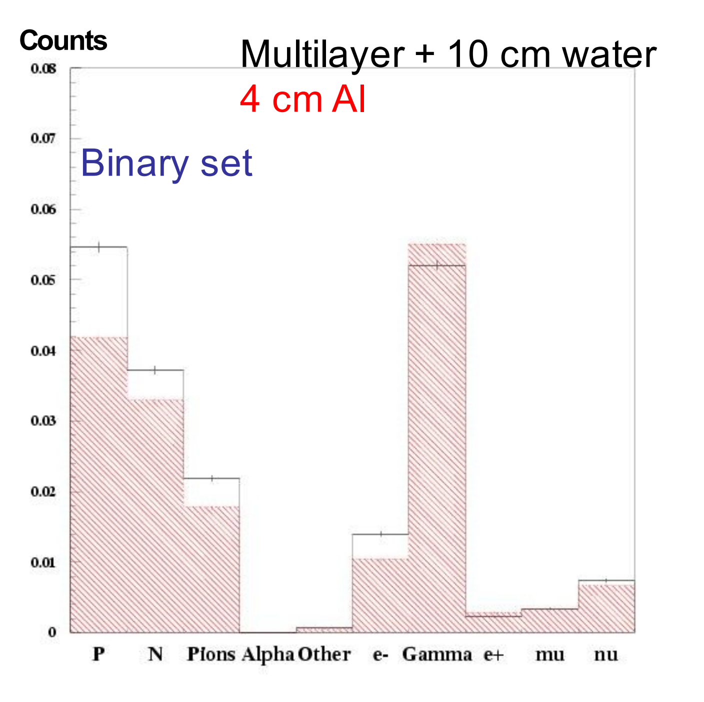
| Shielding material | Energy deposited in phantom (MeV) | | |
|---|---|---|---|
| | EM | Bertini | Binary |
| ML + 5 cm water | 73.5 ± 0.3 | 130.2 ± 0.5 | 119.3 ± 0.4 |
| ML + 10 cm water | 71.9 ± 0.3 | 128.0 ± 0.5 | 117.3 ± 0.5 |
| 4 cm Al | 72.9 ± 0.3 | 127.5 ± 0.5 | 117.0 ± 0.4 |
| 2.15 cm Al | 73.9 ± 0.3 | 130.5 ± 0.5 | 119.3 ± 0.5 |

**An inflatable habitat exhibits a shielding capability equivalent to a conventional rigid one**

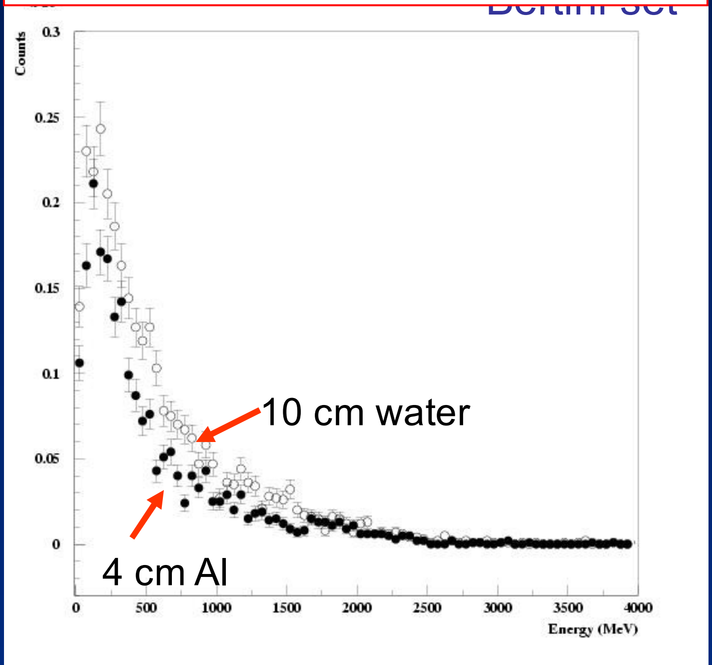
Susanna

# Secondary products in inflatable and rigid habitats

Average no. of secondary particles reaching the phantom




Energy spectrum of secondary protons




Anderson-Darling test
Cramer-von Mises test
$^{2}$ test

Different

No significant effects on the energy deposit in the phantom

# Effects of other cosmic ray components

Similar studies of GCR , C, O, Si and Fe ion components

**Energy deposited in phantom (MeV) by GCR α**
Weighted according to the relative flux w.r.t. p

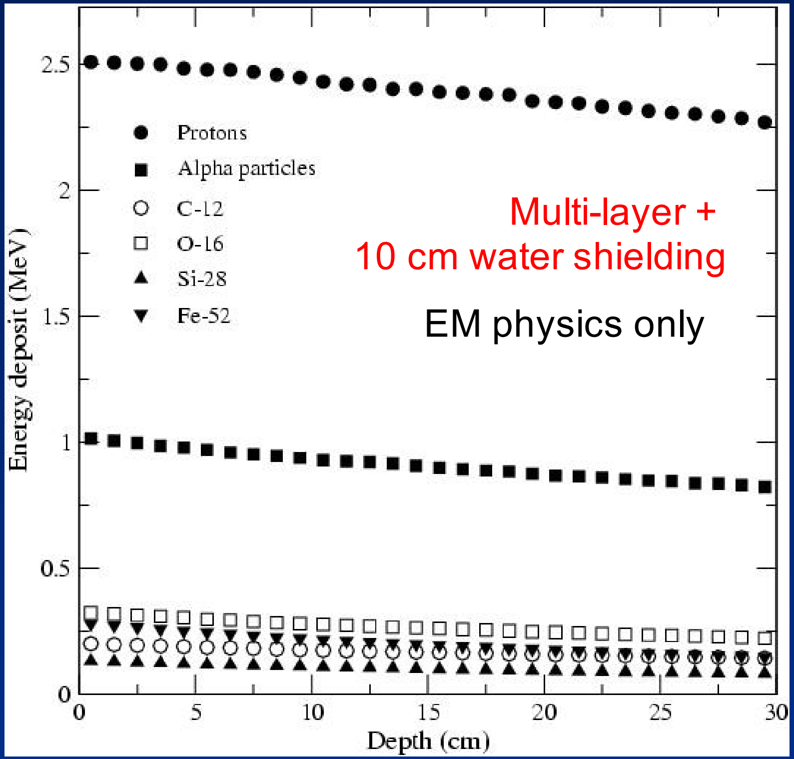
| | Multi-layer + 10 cm water |
|---|---|
| EM | 27.2 ± 0.1 |
| EM + Bertini | 32.0 ± 0.1 |
| EM + Binary | 31.7 ± 0.1 |

Dominant contribution derived from electromagnetic interactions

**First indication**

The hadronic models for α particles are under development and under validation

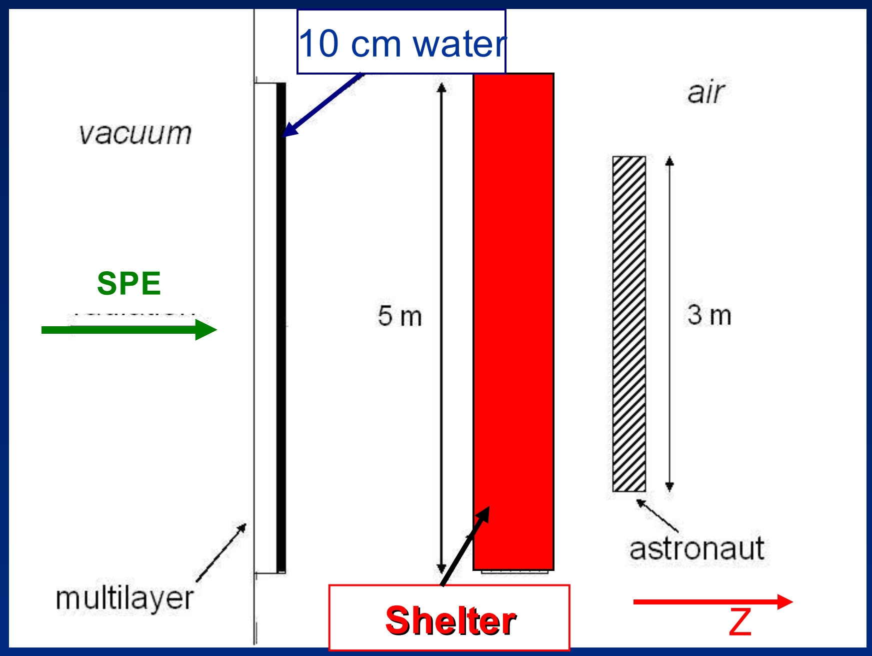
**Average energy deposit of GCR ions**
Weighted according to the relative flux w.r.t. p




Main contribution from p and

# Radiation protection from solar particle events

A shelter protects the crew from the harmful effects of solar particle events



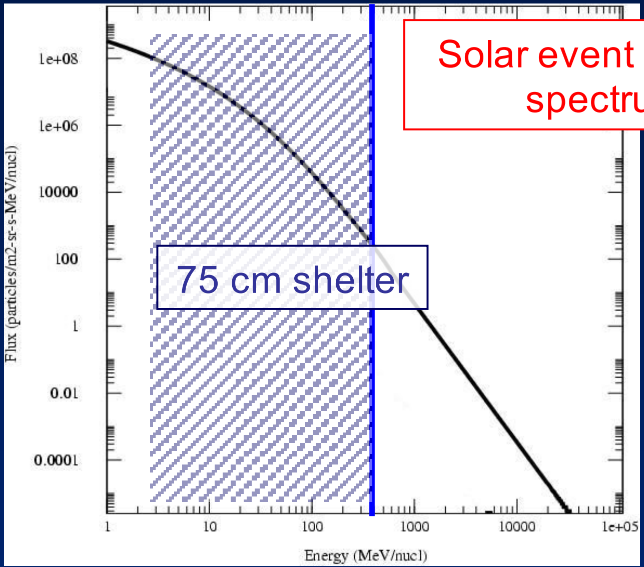

**Shelter:** limited zone enclosed by an additional shielding layer

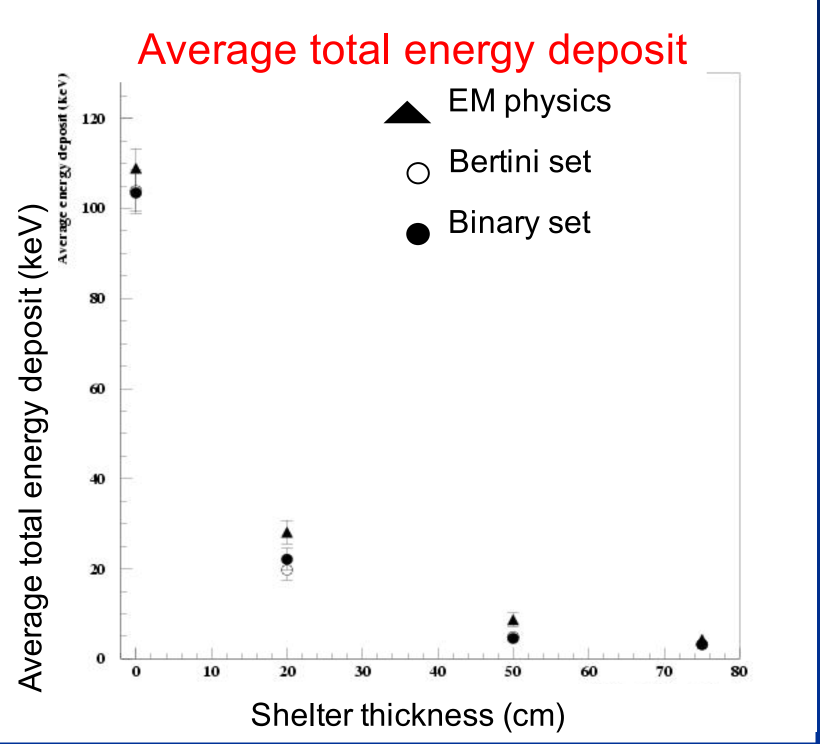
Alarm of a solar particle event ➡ The astronauts recover in the shelter

# Solar particle events

**Fraction of solar event protons reaching the phantom**

| Shelter thickness (cm) | % |
|---|---|
| 0 | $(1.03 \pm 0.05)\ 10^{-1}$ |
| 20 | $(1.6 \pm 0.2)\ 10^{-2}$ |
| 50 | $(3.4 \pm 0.8)\ 10^{-3}$ |
| 75 | $(2.0 \pm 0.6)\ 10^{-3}$ |

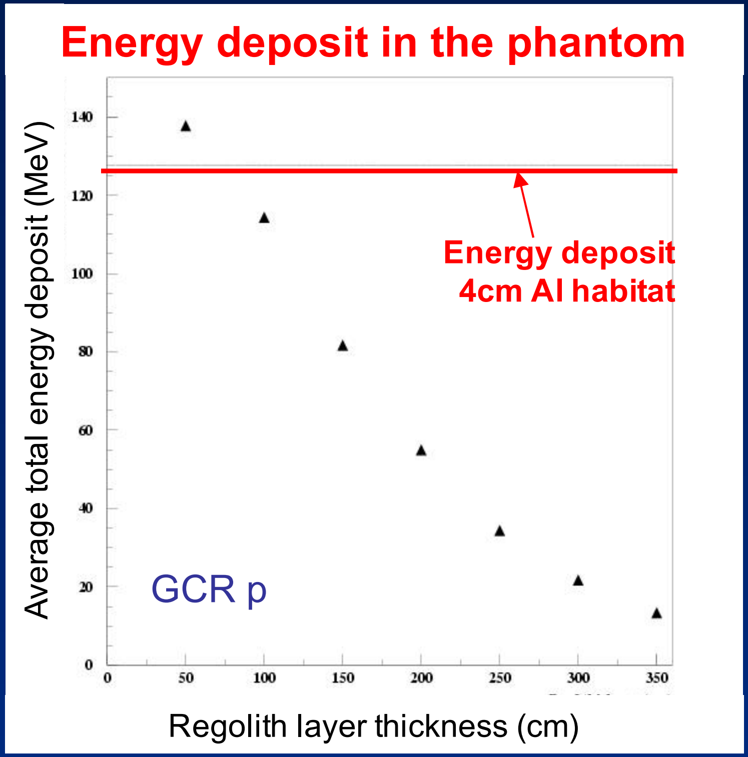


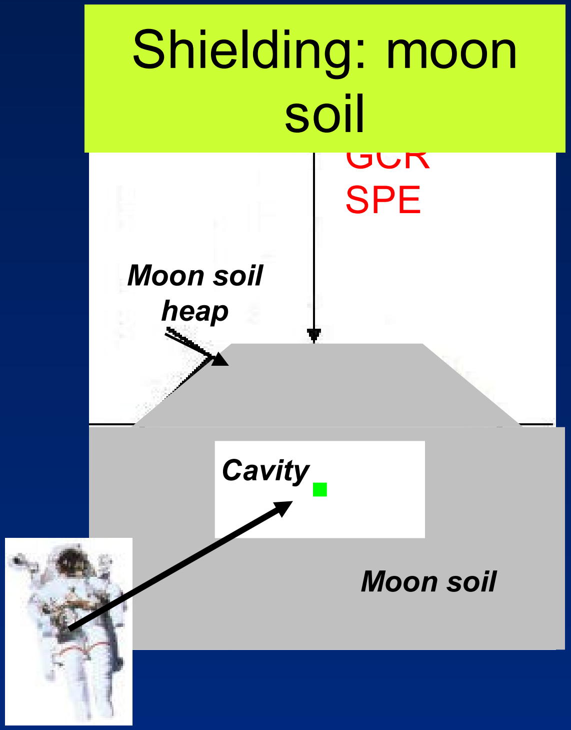




**An additional shelter layer is effective at stopping a significant fraction of solar particle events**

# Radiation shielding on planetary surface

## Moon: intermediate step to a human mission to Mars




**Shielding against GCR**
Lunar regolith shielding is comparable to or better than a conventional Al structure

**Shielding against SPE**
50 cm regolith equivalent to the shielding effectiveness of 50 cm SPE vehicle shelter

Susanna Gu

**Moon regolith can be considered as a shielding option**

# Summary

- **Inflatable Habitat + shielding**
  - Hadronic interactions are significant, systematics is under control
  - The shielding capabilities of an inflatable habitat are comparable to a conventional rigid structure
  - Water / polyethylene are equivalent
  - Shielding thickness optimisation involves complex physics effects
  - An additional shielding layer, enclosing a special shelter zone, is effective against SPE
- **Moon Habitat**
  - Regolith shielding limits GCR and SPE exposure effectively
  - Its shielding capabilities against GCR can be better than conventional Al structures as in the ISS

# Conclusions

- This project represents the first attempt in the European AURORA programme to estimate the radiation protection of astronauts quantitatively
  - Quantitative evaluations
  - Based on open source, validated software
  - Guidance to space industry

- The software system developed is publicly available to the scientific community
  - Advanced software technology
  - Open to extension and evolution

- 1st d[illegible] ESA

Thanks to all REMSIM team members for their collaboration, in particular to:
V. Guarnieri, C. Lobascio, P. Parodi and R. Rampini

**This project was funded by the European Space Agency**